Analysis of a Multiple-Operators Database for MAPOD Study of Ultrasonic Pulse-Echo Response from Side-Drilled Holes

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Abstract. The development of NDT simulation tools allows developing Model Assisted Probability Of Detection. MAPOD requires experimental data to validate modelling choices. We provide in this study multiple-operators data related to the inspection of steel components using contact ultrasound probe. We obtain noise distribution and side-drilled hole responses for two frequencies. The analysis of the variations of the results due to the origin of the operator is presented. We compare results with appropriated statistical laws. First simulations using CIVA code allow introducing the discussion towards the Design of Numerical Experiments. With these data POD points could be obtained. This work is a part of the SISTAE project (Simulation and Statistics for NDE) supported by the French National Research Agency (ANR).

Introduction

In MAPOD approach one of the difficulties is to cope with high level of noise, one of the objectives of this experimental study is to provide data for this kind of situation. We have chosen a specimen of austenitic stainless steel with large grains size, which creates structural noise at low frequency. In this project ten people working at the Laboratoire de Caractérisation Non Destructive are involved: one Responsible for the study, one Principal Operator and eight Operators. Five of them have a long experience in ultrasound applied to NDT, five of them have little experience or no experience in using contact probe measurements.

The first part of the study is driven by the main operator who selects four configurations of testing for all the operators. Then all the results are analysed using the variability of the maximum amplitude measured in a temporal window. The next step is to compare the amplitudes histograms to statistical laws. This work is a part of the SISTAE project (Simulation and Statistics for NDE) driven by the French Atomic Energy Commission (CEA), and supported by the French National Agency for Research (ANR). Within this project the CEA is developing a new POD tool for the software CIVA [1]. We conclude this study by presenting some simulations results using CIVA. The future work will be to compare in details how experimental variability measured in this study could be obtained by simulation.

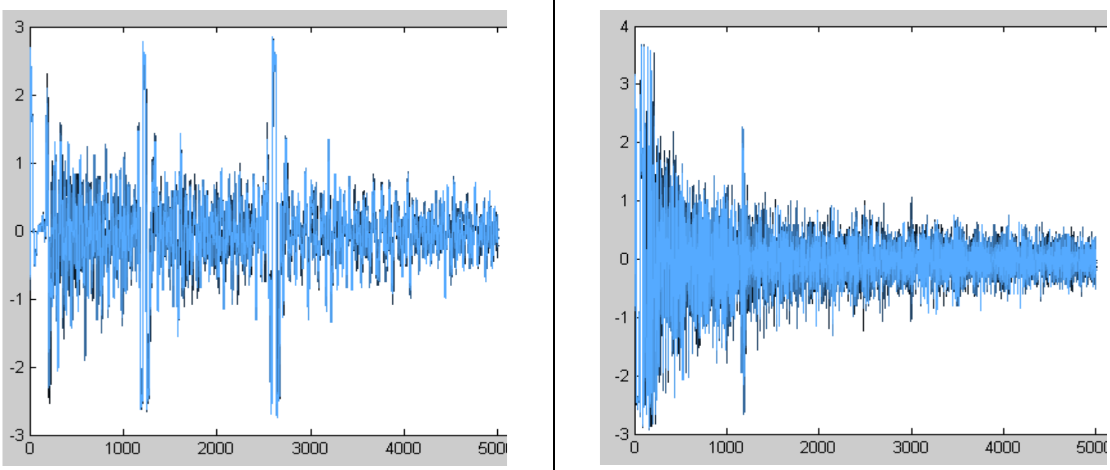
Experimental Set-Up : Side-Drilled Holes inspected with contact probes

The experimental set-up has been chosen to reduce the number of influent parameters for ultrasonic measurements. The operators do not have the possibility to modify the ultrasonic generator settings and the sampling choices for signal acquisition. Settings are not designed to be the most effective for each hole but to ensure a good detection of all the holes in the specimen if possible. Signal windowing will be done after if necessary by the principal operator for detailed analysis. The table 1 indicates all the various depths for this study, holes having 2.5 mm diameter.

Hole	Depth (mm)	Hole	Depth (mm)
1	2.5	**10**	38
2	8	**11**	44
3	13	**12**	48
4	17.5	**13**	50
5	18	**14**	54
6	22.5	**15**	54.5
7	23	**16**	58
8	28	**17**	63
9	34	**18**	68.5

Table 1. Holes depths

The figure 2 shows fifteen superimposed signals that allow to see somewhat the noise envelope. The noise is relatively high in our sample at 2.25 MHz. At 5 MHz the attenuation is high enough to make the backwall echo disappear.



15 signals at 2.25 MHz

15 signals at 5 MHz

Figure 2. Example of 15 superimposed signals on hole # 9

The variability of the signal is firstly studied with the main operator. He acquired a series of fifteen signals and repeated the acquisition process four times at various days and time period. The probe is lifted off the surface of the sample so the coupling should be re-obtained for each signal. The variability is firstly studied using standard deviation of the mean value. We develop also our own criterion. The result of the total range of the histograms (difference between maximum and minimum) for each signal series divided by the mean value of all series is called the histogram variability. The histogram variability reveals to be more sensitive than the standard deviation to express the variations of the signal measurement. With these two criteria, four experimental configurations are selected for the multiple-operators study: two amongst the lowest variable cases, and two amongst the worst.

Comparison of the results variability

Ten operators participated to the campaign. All people are working at the LCND laboratory. Five of them have a long experience in ultrasound: several years to more than 20 years. The other five people have a little experience in contact probes and ultrasound: at best less than several months.

The figure 2 is a synthesis of the results. The vertical axis is the histogram variability. The two cases with low variability corresponds to hole 3 at 2.25 MHz and 5 MHz. For the two holes closest to the surface (holes 1 and 2) it was not possible to separate the surface echo from the side-drilled holes echoes. The two holes with high variability are the hole # 15 at 2.25 MHz and the hole # 9 at 5 MHz. For the deeper holes at 5 MHz, the defect signal was not separated from the noise.

The results are in good accordance with previous results reported in various studies. The operators closely related to the study obtained good results as they were deeply implied in the results and took a great care during their acquisitions. One of the operator had some very high variability: a variability of 1.4 corresponds to a variation of 140 % between maximum and minimum values in comparison with the mean value. This operator was also one of the less experimented. This biggest variation is probably due to holes proximity, so that the operator had undoubtedly acquired a signal from a wrong hole. This illustrated one of the possible artefacts of this kind of study where the number of defects is too high in comparison with in situ inspection. The two operators with too disperse results are not taken into account for the final table (Table 2).

As expected the variability increases with the decreasing of Signal to Noise Ratio. The mean result of the five more experimented operators are always better than the less experimented operator, but one of the less experimented operator obtain very good results.

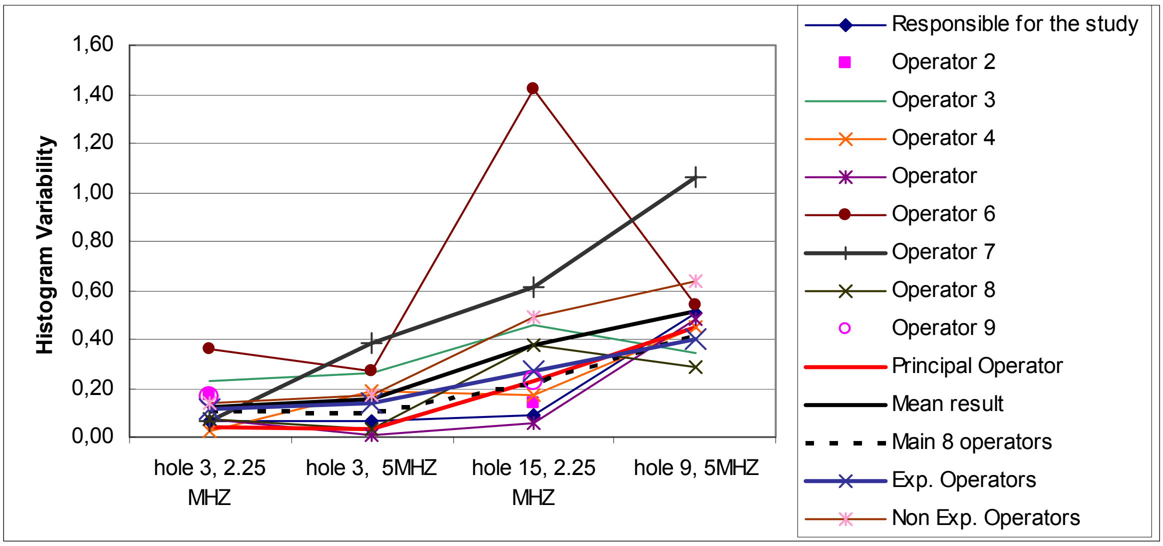


Figure 2. Analysis of the histogram variability

The table 2 recalls the mean variability of the results obtained by the eight main operators. The conclusion is that the variability could be quite high in case of high level of noise even in the case of laboratory studies. These results will enable to produce fitting data for numerical studies aiming at POD calculations (see last paragraph)

	hole #3 2.25 MHz	hole #3 5MHz	hole #15 2.25 MHz	hole #9 5MHz
Main 8 operators	10,5%	9,8%	22,4%	42,0%

Table 2. Variability of the results obtained by the 8 main operators

It is important to note that the histogram variability (figure 2) has not to be compared with the variability of a POD. If we had defined a threshold to decide when a defect is present or not, the variability of the answer would have been lower.

Comparison to Appropriated Probability Density Function

A second objective of this study was to acquire enough data to describe statistically the noise and the hole signals, and to compare them to the distribution of amplitudes with a probability density function.

Using all the data acquired by the ten operators, we obtained two hundred and twenty five values of the signal maximum for side-drilled holes.

We used a spatial averaging method to obtain representative histograms of the maximum of the noise signals. The space between two acquisitions was equal to the probe diameter divided by 2. We made an X-Y displacement of the probe. A temporal windowing was also made to suppress surface and backwall echoes. One hundred signals were obtained with the two probes at 2.25 MHz and 5 MHz. The corresponding histograms are represented on the figure 3, using the Sturges's law to calculate the number of bins of the histograms: 8 bins for 100 values and 9 bins for 225 values.

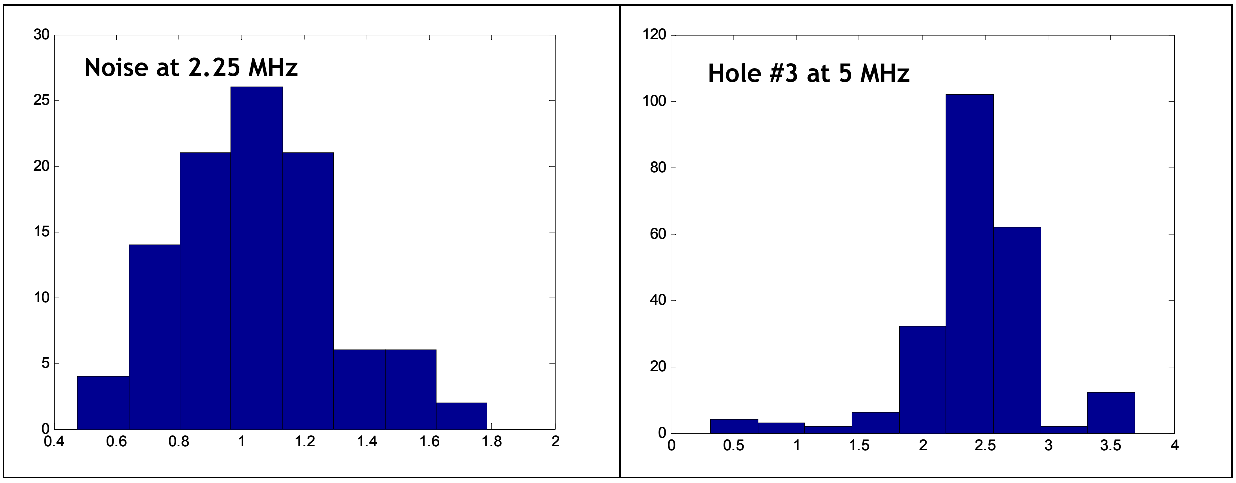


Figure 3. Example of histograms (maximum amplitude of noise signals and hole signals)

Several studies proposed different probability density functions to describe, for example, the maximum of the signal envelope in a time window. This kind of calculus is not so trivial as it is not simply calculated for a given time. A global description of distribution modelling had been proposed by Thompson and Margetan [2].

The histogram of the maximum amplitude of the noise seems to be best fitted by a Gaussian distribution:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \tag{1}$$

Using Matlab tools our fitting to a Normal Distribution gave the following estimated parameters: the mean is equal to 1.05 and the standard deviation is equal to 0.25. In figure 4 we illustrate the variability of the histograms when we have only one hundred values. In red we represent the data histograms, in blue we represent three realisations of statistical law using estimated parameters. The values are redistributed in common intervals to compare histograms using Sturges law (8 bins). The minimum value of the noise is 0.476 and the maximum value is 1.786.

The distribution of the maximum amplitudes of the hole signals fits very well with a Rician law :

$$P(x) = \frac{x}{\sigma^2} \exp\left(\frac{-(x^2+\upsilon^2)}{2\sigma^2}\right) Io\left(\frac{x\upsilon}{\sigma}\right) \tag{2}$$

The estimated Rician parameters are $\nu = 2.3577$ and $\sigma = 0.500$. In figure 4 the corresponding histograms are plotted with 9 bins. The minimum value of the hole signal is 0.32 volt and the maximum value is 4.15 volts.

The distribution of the maximum value for the hole signal is clearly thinner than the distribution of the noise. All of these results are in good agreement with the literature results.

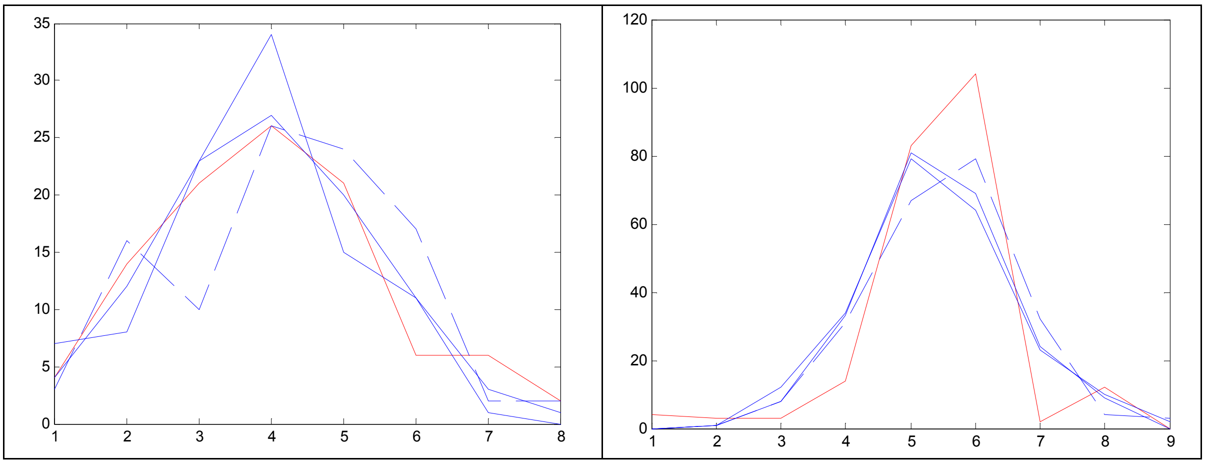


Figure 4. Example of histograms (maximum amplitude of noise signals and hole signals)

First simulations: towards Design of Numerical Experiments and POD Curves fitting

The study shows that some big variations in signals occurred even in laboratory conditions when noise begins very high. The Signal to Noise Ratio of hole # 9 at 5 MHz is about + 3 dB. In this study we begin some simulation work with the CIVA software [3] to understand the origin of the variations of defect signal. The objective is to be able to reproduce this kind of variation when POD simulation would be done. Various parameters could be modified using CIVA. The table 3 gives the parameters we modified in this first approach.

PARAMETERS	Amplitude (a.u.)	Var. in %
All parameters (perfect testing)	**774,65**	
All perfects parameters except coupling path (0.05mm)	785,11	1
All perfects parameters except inclinaison angle path (-0.5°)	201,46	-74
All perfects parameters except bigle angle path (1°)	9,0698	-99
All perfects parameters except X position (-2 mm)	229,24	-70
All perfects parameters except frequency (2.275 MHz)	556,48	-28

Table 3. Sensitivity of different modelling parameters

When the operator repeats his measurement, he modifies mainly the position of the transducer (X position), and the coupling (coupling path). As the hole length is about the same size of the probe we do not consider in simulation a change along the Y axis. Border effects are taken into account in the simulation by defining the hole position and length as in the real sample. We introduce also in the simulation a variation in the bigle and the inclination angles, and also in the central frequency to reproduce the transducer variations (as if we had to change the transducer). The column Amplitude (arbitrary unit) indicates the value of the simulation when modifying one of the five selected parameters. In such a study, towards design of Numerical Experience, the difficulty would be to find cross-correlation between parameters. Angle parameters are very sensitive as expected; more surprising is the sensitivity of the central frequency. One of the difficulties of the simulation is to reproduce coupling variation. The length of the coupling path does not vary a lot and could not reproduce the real effect as shown in table 3. The origin of the variation of the coupling is the surface roughness. In our experiments the surface roughness is very good as we have a machined surface, but this roughness is enough to "stop" the probe displacement, creating variations in the signal amplitude as the pressure applied on the probe varies. In future works, this aspect of the variation should be taken into account in another way in simulation.

The data obtained in this study allow calculating the points of a POD curve. Two solutions are possible. The quickest one is to use raw data. For example in the case of the hole # 9 at the frequency 5 MHz with a threshold of 1.9 volts, we obtain a Probability of False Calls of 4 %, a Probability of Non Detection of 19,4 % and a Probability of Detection of 80,6 %. The second solution would be to use the probability density function after fitting process, as illustrated on the figure 4.

Conclusion

This study brings a lot of data to compare POD modelling with real experiments. Despite some reserves due to the limitations of a laboratory study, the work allows discussing modelling results (from CIVA software for example) in details. This study does not take into account other important parameters in POD studies such as the time pressure or the influence of the organization [5].

The objective is now to continue to compare experimental results to simulation calculation, to propose some rules to introduce variability in the modelling of the NDE inspection using UT contact probes.

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